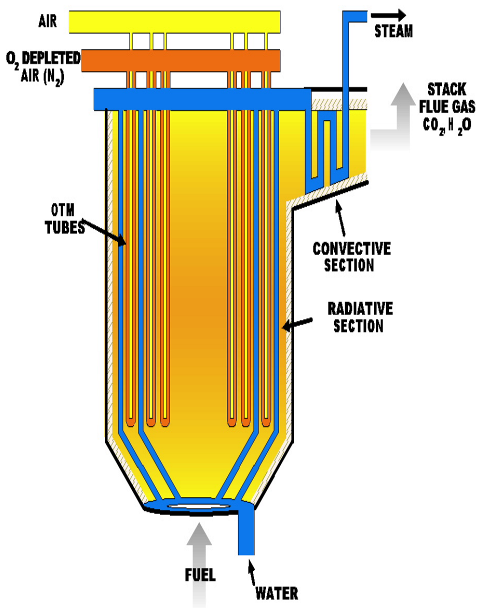
3.0 CAPTURING AND SEQUESTERING CARBON DIOXIDE

3.1. GEOLOGIC SEQUESTRATION

3.1.1 CO_2 CAPTURE AND SEPARATION

Technology Description



Oxyfuel Technology

Integrates air separation, using O2 Transport Membrane (OTM) and oxygen combustion

Fossil- and biomass-based energy conversion processes convert hydrocarbon materials (i.e., substances consisting mostly of carbon and hydrogen) into carbon dioxide and water while releasing energy. The goal of CO_2 capture and separation is to produce relatively pure CO_2 from these processes, preferably at pressures suitable for storage or reuse.

System Concepts

- *Post-combustion capture*. A chemical or physical separation process extracts CO_2 from the flue gas of a conventional air-fired combustion process. CO_2 is present in concentrations ranging from 3% to 12%. The focus is on technology for retrofitting or repowering existing power plants and industrial processes.
- *Oxy-fuel combustion.* Pure oxygen rather than air is charged to the combustion chamber, producing a flue gas of CO_2 and water. A portion of the CO_2 is recycled and mixed with the oxygen to absorb heat and control the reaction temperature.
- *Precombustion decarbonization*. The hydrocarbon feedstock is gasified to produce a synthesis gas made up primarily of hydrogen and carbon dioxide. The CO_2 is separated from the hydrogen before it is combusted or charged to a fuel cell.
- There are other advanced-system concepts in which fuel processing and CO_2 capture are integrated into a single stage using, for example, membranes or reduction-oxidation agents.

Representative Technologies

- The conventional technology for post-combustion capture (removing CO_2 from flue gas) is amine scrubbing. A solution of amine and water is contacted with flue gas. The amine and the CO_2 undergo a chemical reaction forming a rich amine that is soluble in the water. The rich amine solution is pumped to a desorber where it is heated, reversing the reaction and releasing pure CO_2 gas. The recovered amine is recycled to the flue-gas contactor.
- Other technologies for post-combustion capture include cryogenic distillation, polymer membranes, ceramic membranes, carbon absorbents, sodium absorbents, hydrides, and lithium silicate.

Technology Status/Applications

- Amine systems are used in numerous industrial applications to capture CO_2 from flue gas for use as a commodity chemical. Cryogenic and carbon absorbent systems have been built commercially.
- Other post-combustion capture technologies are being developed at the laboratory and pilot scale.

Current Research, Development, and Demonstration

RD&D Goals

- In the long term, reduce the cost of capture so that it increases the cost of energy services by 10% or less.
- By 2005, reduce the cost of capture by 50% in retrofit applications. Attainment of 2005 goals will be estimated based on technology performance in pilot-scale proof-of-concept demonstrations.
- Conduct large-scale demonstration of new technology by 2010.

RD&D Challenges

- CO_2 exists in air-combustion flue gas at low concentration, 3-12 volume percent.
- Flue gas contains reactive impurities that can adversely affect CO_2 capture systems.
- Transport and/or storage systems may require highly pure CO_2 product.
- Loss of CO_2 temperature and pressure across the capture system.

RD&D Activities

- Laboratory-scale experiments with advanced amines, ceramic membranes, high-temperature polymer membranes, vortex gas/liquid separator, ammonium bicarbonate, carbon absorbents, and electrochemical pumps.
- Pilot-scale tests with a novel oxy-fuel boiler, a CO_2/water hydrate process, a sodium-based CO_2 sorbent, and a metal reduction-oxidation power generation process.

Recent Progress

- During a short three-year period, a strong portfolio of research projects has been developed with more than 40% private-sector cost-share.
- The international community has been successfully engaged through participation in the International Energy Association Greenhouse Gas Programme, the CO_2 Capture Project with the European Commission and other international participants, and other collaborations with Canada, Australia, and Japan.

Commercialization and Deployment Activities

- Roughly 15 Mt/yr of CO_2 is captured from anthropogenic emissions sources in the United States and used as a commodity chemical.

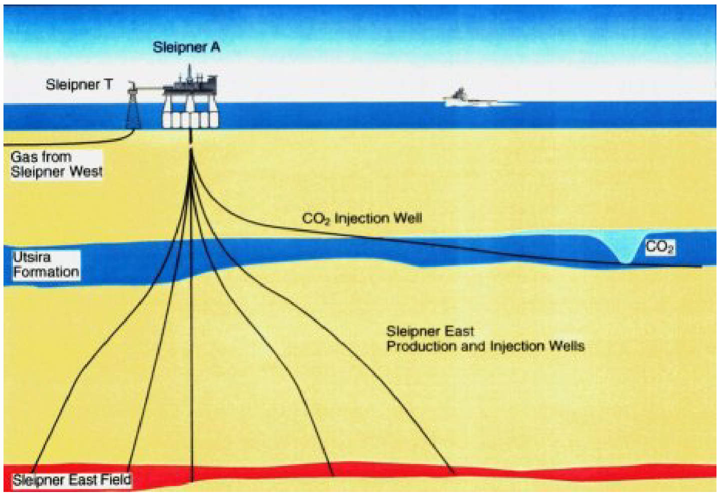
Market Context

- Development of approaches for economically decarbonizing fossil fuels will allow the carbon-free production of electricity and hydrogen, and will take advantage of an existing fossil fuel infrastructure that accounts for more than 80% of the energy consumed in the United States and internationally.

3.1.2 CO_2 STORAGE IN GEOLOGIC FORMATIONS

Technology Description

Sleipner North Sea Project



Large amounts of CO_2 (about a billion tons per year) may need to be stored as a part of a future global atmospheric stabilization strategy. CO_2 can be injected into depleting oil wells and unmineable coal-bearing formations to enhance resource recovery. A portion of the CO_2 remains underground, although current industry practices are geared strongly toward minimizing the CO_2 left underground – and little or no attention is paid to the CO_2 that is not recovered. R&D is focused on revamping conventional enhanced oil recovery and enhanced coalbed methane processes so that they can serve a dual purpose: resource recovery and CO_2 storage. Saline formations, organic-rich shale beds, and other nonconventional geologic structures have potentially enormous CO_2 storage capacities. Research is focused on learning more about these formations and developing the capabilities needed to use them as CO_2 repositories.

System Concepts

- CO_2 is captured from a large point source of anthropogenic emissions, transported, and injected into a depleting oilwell, unmineable coal seam, saline formation, depleting gas well, shale formation, or other geologic structure amenable to CO_2 storage.
- Storage may entail geochemical reactions that tend to form carbonates in silicic host rock, enhancing containment.
- In an oil well, the CO_2 decreases the viscosity of the oil, enabling more of it to be recovered. A portion of the injected CO_2 remains stored in a reservoir as a free gas, brine or oil solution, or carbonate.
- In a coal bed, CO_2 displaces methane absorbed onto the surface of the coal, enabling it to be recovered. The CO_2 remains absorbed on the coal and, thus, is securely stored.
- Components in the CO_2 stream (e.g., sulfur, nitrous oxides, nitrogen) could have a positive impact on certain storage applications.

Representative Technologies

- Natural gas storage in saline aquifers provides relevant capability.
- Technologies will borrow extensively from the petroleum industry in the areas of drilling simulation; completion of injection wells; processing, compression, and pipeline transport of gases; operational experience of CO_2 injection for enhanced oil recovery; and subsurface reservoir engineering and characterization.

Technology Status/Applications

- The Mount Simon reservoir underlying Illinois, Indiana, Michigan, Kentucky, and Pennsylvania has been approved for industrial waste disposal and underlies a region with numerous fossil energy power plants.

- Industry has experience with more than 400 wells for injecting industrial wastes into saline formations.
- The petroleum technology is readily adaptable to subsurface CO_2 storage.

Current Research, Development, and Demonstration

RD&D Goals
- Develop domestic CO_2 underground storage repositories capable of accepting around a billion tons of CO_2 per year.
- Demonstrate that CO_2 storage underground is safe and environmentally acceptable.
- Demonstrate an effective business model for CO_2 enhanced oil recovery and enhanced coalbed methane, where significantly more CO_2 is permanently stored than under current practices.
- Develop publicly accepted monitoring protocols.

RD&D Challenges
- Develop the capability to inject CO_2 into saline formations with low permeability.
- Harness geochemical reactions to enhance containment.
- Develop injection practices that preserve cap integrity.
- Develop an understanding of the CO_2 properties of shales and other unconventional hydrocarbon-bearing formations.
- Develop the ability to track CO_2 transport.
- Develop field practices that optimize CO_2 storage and resource recovery.
- Develop the ability to predict the CO_2 storage capacity and potential resource recovery of a particular formation.
- Develop the ability to track the fate and transport of injected CO_2.
- Develop a better understanding of the chemistry of coal and CO_2, and conduct comprehensive R&D program on all physical and chemical aspects of CO_2 interactions with reservoir phases.

RD&D Activities
- Study geochemical reactions involving CO_2 in a laboratory.
- Study the natural analogs of geochemical CO_2 conversion. Study rock samples from CO_2 bearing geologic formations to better understand in situ geochemical/geobiological reactions.
- Develop CO_2 tracking technology, e.g., sonic, chemical tracers.
- Study CO_2 transport in the Sleipner Vest gas field, via the International Energy Agency's Greenhouse Gas Programme.
- Novel injection techniques to increase CO_2 storage in saline formations.
- CO_2 storage in coal beds. ARI and industry consortium, commercial-scale field demonstration in the San Juan Basin; Consol – horizontal drilling, Alabama geologic survey, screening model for Black Warrior.
- CO_2 storage in oil reservoirs. Weyburn, reservoir mapping, West Pearl Queen, CO_2 monitoring and simulation.

Recent Progress
- Major saline formations underlying the United States have been identified.
- Initiated a pilot-scale test of CO_2 storage in a depleted oil reservoir.
- Initiated several field tests with key industrial companies participating and providing cost-share: Consol Inc. CBM,-Appalachia ARI, CBM-San Juan Basin; Strata Production C. – Permian Basin; Pan Canadian Resources EOR-Canada.

Commercialization and Deployment Activities
• Since 1999, Statoil has been injecting CO_2 at a rate of 1 Mt/yr into the Sleipner Vest gas field in a sandstone aquifer 1,000m beneath the North Sea. • About 70 oil fields worldwide use CO_2 for enhanced oil recovery. • Another project uses CO_2 from Dakota Gasification for enhanced oil recovery in the Weyburn field in Canada. CO_2 is transported via pipeline. • The pipeline enables extensive use of CO_2 for enhanced coal bed methane recovery in the San Juan basin. • There are plans for using CO_2 for enhanced oil recovery in Kansas, using CO_2 from ethanol production. **Market Context** • Development of approaches for economically decarbonizing fossil fuels will allow the carbon-free production of electricity and hydrogen, and will take advantage of an existing fossil fuel infrastructure that accounts for more than 80% of the energy consumed in the United States and internationally.

3.1.3 NOVEL SEQUESTRATION SYSTEMS

Technology Description

In the long term, CO_2 capture can be integrated with geologic storage and/or conversion. Many CO_2 conversion reactions are attractive but too slow for economic chemical processes.

System Concepts

- Using impurities in captured CO_2 (e.g., SO_x, NO_x) or additives enhances geologic storage. This is a possible opportunity to combine CO_2 emissions reduction and criteria pollutant-emissions reduction.
- Conducting reactions on CO_2 while it is being stored underground can alleviate the problem with slow kinetics.
- Rejected heat from electricity generation and CO_2 compression can help drive CO_2 conversion process.

Representative Technologies

- Capture of CO_2 from flue gas and algal conversion to biomass.
- Capture of CO_2, storage in a geologic formation, and in situ biological conversion to methane.

Technology Status/Applications

- Conceptual.

Current Research, Development, and Demonstration

RD&D Goals

- Demonstrate viable chemical or biological conversion approaches at the laboratory scale.
- Develop robust conceptual designs for integrated capture, storage, and conversion systems.

RD&D Challenges

- CO_2 conversion reaction kinetics are slow, energy requirements are high.
- For biological in situ CO_2 conversion, must provide food and remove waste.
- Truly novel concepts may be required to meet the ultimate "stretch" goals of the program. Technology breakthroughs could come from concepts associated with areas not normally related to traditional energy technologies (e.g., nanotechnology). Tapping areas where current researchers do not have an energy mindset will require new approaches for soliciting proposals for R&D projects.

RD&D Activities

- Laboratory and pilot-scale experiments with biological and chemical conversion.
- Conceptual studies of integrated systems and in situ CO_2 conversion.

Recent Success

- Several cost-shared research projects have been initiated.

Commercialization and Deployment Activities

- None.

3.2. TERRESTRIAL SEQUESTRATION

3.2.1 LAND MANAGEMENT

3.2.1.1 CROPLAND MANAGEMENT AND PRECISION AGRICULTURE

Technology Description

Cropland management practices can increase the amount of carbon stored in agricultural soils by increasing plant biomass inputs or reducing the rate of loss of soil organic matter to the atmosphere as CO_2. Precision agriculture is a form of site-specific management used to increase productivity. This approach can be adapted for improving soil carbon sequestration through a customized carbon sequestering management plan.

System Concepts

- Each production system will have its own particular set of practices that optimize carbon sequestration while maintaining profitable crop production.
- Precision agriculture can be used to develop the most appropriate suite of technologies for specific sites.
- Most agricultural soil management practices that promote carbon sequestration provide additional environmental and yield benefits.
- Use of genetically modified crops to enhance yields and reduce fertilizer use.

Representative Technologies

- Conservation tillage, especially no-till.
- Residue management.
- Reducing fallow.
- Cover crops.
- Nutrient management.
- Manure and organic matter additions.
- Water management.
- Erosion control.
- Apply advanced information technologies (e.g., global positioning systems, remote sensing, computer modeling) for efficient application of management treatments.
- Herbicide-tolerant crops that advance conservation tillage.
- Genetically modified crops that increase utilization of soil nutrients and/or fertilizer.
- Technologies that increase agricultural productivity (e.g. by increasing yields, minimizing crop losses, minimizing spoilage and increasing shelf life, because each would minimize area under cultivation).

Technology Status/Applications

- Each of these technologies and management practices has been researched and implemented for purposes other than carbon sequestration (for soil conservation, erosion control, and crop yield increases).
- Soil carbon data has been collected from hundreds of long-term field studies and used to estimate the soil carbon sequestration potential of different management practices.
- Additional studies are underway to explicitly investigate the potential of various management practices to sequester soil carbon.
- Technical support is available on how to implement these technologies for conservation and yield-enhancing purposes.
- Specialized equipment for implementing management practices (no-till drills, global positioning systems, etc.) is commercially available.

Current Research, Development, and Demonstration

RD&D Goals

- Quantify the carbon sequestration potential of each technology and management practice for various crop production systems, climates, and soils.
- Develop the combinations of practices that optimize soil carbon sequestration, crop production, and profits for various crop production systems; soil types; and geographical areas.
- Determine the applicability of precision agriculture for enhancing carbon sequestration.

- Develop decision support tools for farmers, other land managers, and policy makers that provide guidance for land-management decisions. For example, create databases that answer questions about how changing from one land-use practice to another will affect carbon sequestration, production, and profits.

RD&D Challenges

- Measuring and monitoring procedures need to be improved for more accurate determination of cropland soil carbon status.
- Increasing cropland soil carbon without increasing emissions of other greenhouse gases, especially nitrous oxide and methane.
- Research on the effect on carbon sequestration of specific management practices, climate and weather factors, soil properties, and cropping systems is needed to develop recommendations and improve models and decision support tools.

Recent Progress

- Research programs have been established in the USDA (Carbon Cycle Component of Agriculture Research Service's Global Change National Program), Consortium for Agricultural Soils Mitigation of Greenhouse Gases, DOE Office of Fossil Energy, and U.S. Geological Survey to conduct research on soil carbon sequestration.
- More data are becoming available to improve the quantification of the cropland carbon sequestration.
- Preliminary models and decision support systems have been developed.
- Research on precision agriculture has been initiated.

Commercialization and Deployment Activities

- Carbon sequestration markets are being developed.

Market Context

- Ranges from 10%-80 % of cropland acreage.

3.2.1.2 CONVERTING CROPLANDS TO RESERVES AND BUFFERS

Technology Description

Converting croplands to other less-intensive land uses such as conservation reserve and buffer areas increases soil carbon because soils are not subjected to tillage and other disturbances that lead to soil carbon losses.

System Concepts

- Conversion of croplands to reserves and buffers provides environmental benefits by removing potentially degradable land from production, but competes with crop production needs and markets.
- Reserves receive minimal long-term management and may be converted back to cultivation.
- Soil carbon can be rapidly lost if reserves or buffers are converted back to cultivation.
- Reduce land under cultivation, which then would directly or indirectly free up land for conservation purposes.

Representative Technologies

- *Conservation Reserve Program*. Converts cropland in environmentally sensitive areas to grass or forest land for a contractual time period (e.g, 5-15 years).
- *Riparian Buffers.* Land adjacent to streams is converted from cropland into grass and forest land.
- Technologies that increase agricultural productivity (e.g. by increasing yields or minimizing spoilage and increasing shelf life, because each would minimize area under cultivation.

Technology Status/Applications

- Almost 34 million acres of land have been entered into the Conservation Reserve Program as of 2002.

Current Research, Development, and Demonstration

RD&D Goals

- Quantify the carbon sequestration potential of buffer and reserve programs for various climates and soils.
- Develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of reserves and buffers.
- Develop decision support tools for farmers, other land managers, and policy makers to inform which areas to put into reserves and the relative costs and benefits of different land conservation approaches, both in terms of carbon sequestration and production.

RD&D Challenges

- Improve measuring and monitoring procedures for more accurate carbon status.
- Determine the effects of conservation reserves on non-CO_2 greenhouse gases.
- Develop the optimal combination of practices for each system for each area of the country and soil type.
- Develop better models and decision support systems.

Recent Progress

- Estimates of the potential for reserve and buffer area soils to sequester soil carbon have been published and provide a baseline for future activities.
- Ongoing programs have been established in USDA to promote and assist in buffer and conservation reserve programs.
- Preliminary models and decision support systems have been developed.

Commercialization and Deployment Activities

- USDA has an established Conservation Reserve Program and riparian buffer program.
- Technical support is available from USDA on how to implement technologies and practices.

Market Context

- The market for implementing land conservation through reserves and buffers will be driven by other conservation priorities such as erosion control and water quality, and crop commodity prices.

3.2.1.3 ADVANCED FOREST AND WOOD PRODUCTS MANAGEMENT

Technology Description

Advanced forest and wood products management represent large carbon sequestration opportunities that can also produce other environmental benefits, such as improved water quality and habitat. Advanced technology is also needed to improve forest and wood product management in these areas: (1) data collection, assimilation, and analysis, (2) design, development, and management of forest systems, and (3) deployment of acceptable operations. Information systems are needed for collecting and using increasingly detailed site-specific data. Traditional silvicultural tools need to be integrated with newer technologies to better design and manage forest production. In addition, these systems provide for improved understanding, control, and manipulation of woody tree growth, resource requirements and acquisition, and microbial processes that control carbon, water, and nutrient flows. Energy-efficient, low-impact systems will be developed and used to apply treatments optimized to achieve specific resource outcomes. Durable wood products in use and wood disposed of in landfills can provide a mechanism to allow forestlands to continually add to and increase the amount of sequestered carbon. Advances in developing wood products, substitutions, recycling technologies, and wood waste management provide pathways to increase carbon sequestration. These systems provide an integrated capability to improve environmental quality while enhancing economic productivity by increasing energy efficiency, optimizing fertilization and other site treatments, and conserving and enhancing soil and water resources.

System Concepts

- Global positioning, measurement infrastructure, and remote and in situ sensors for soil, plant, and microclimate characterization and monitoring.
- Process-based growth models, data, and information analysis.
- Variable-rate application control systems and smart materials for prescription delivery.
- Advanced management systems for wood products in use and in landfills and advanced wood products development.
- Low-impact, energy-efficient access and harvest systems.

Representative Technologies

- Integrated forest carbon dynamics, inventory, modeling, and prediction systems.
- Global positioning satellites and ground systems, satellite and aircraft based remote sensing, in situ electrical, magnetic, optical, chemical, and biological sensors.
- Advanced information networking technologies; autonomous control systems; selected and designed genetic plant stock; materials responsive to soils, plants, moisture, pests, and microclimates.
- Biological and chemical methods for plant and microbial process manipulation.
- Wood product development, substitution, and management pathways.

Technology Status/Applications

- Many first-generation precision technologies can be used in silvicultural systems, especially in plantations with little modification. Application to mixed-age and/or mixed-species forest types will require additional research. LIDAR and RADAR remote-sensing methods are being tested for 3-D imaging of forest structure.
- Information management and networking tools; rapid soil monitoring and characterization sensors; tree stress and growth sensors; systematic integration of all technologies are not yet available for application to silvicultural projects.
- Understanding of soil nutrient processes exists in the forestry, energy, and university research communities.
- The capability exists for genetic characterization performance testing of plant stocks, developing smart materials, and methods for microbial manipulation.

Current Research, Development, and Demonstration

RD&D Goals

- Technologies that improve silviculture operation efficiencies and reduce energy consumption from road building to milling processes and transportation.
- Economic and biophysical modeling to better understand the economics of achieving certain GHG mitigation goals through tree planting and improved forest management.

- Remote and field deployed sensors/monitors and information management systems for accurate, real-time monitoring and analysis of plant growth, soils, water, fertilizer, and pesticide/herbicide efficiency.
- Smart materials for prescription release.
- Advanced fertilizers and technologies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs.
- Methods of manipulating system processes to increase efficiency of nutrient availability and uptake to increase CO_2 uptake and sequestration and reduce emissions.
- Wood product management and substitution strategies.
- Initial systems models and prototype operation on major plantation types by 2007.
- Deploy first-generation integrated system models and technology by 2010.

RD&D Challenges

- Site-specific silviculture requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time water and nutrient demand characterization, photosynthesis and allocation characterization, and insect and pest infestation characterization; autonomous control systems; and integrated physiological model and data/information management systems, as well as efficient, low-impact access and harvest systems.
- Smart materials that will release chemicals based on soil and plant status depend on breakthroughs in materials technology.
- Improved understanding of forest processes is required to support development of management systems.
- Couple plant physiology and soil process models and improving the temporal resolution of process representation.
- Improve understanding of the pathways by which methane is produced and consumed in soils, and by which nitrate is reduced to gaseous nitrogen, which is required to support scaling trace gas emissions.
- Research on sensors, information sciences, materials, and above- and below-ground forest processes.

RD&D Activities

- Efforts are underway in both public and private sectors.
- Sponsors include USDA, universities, forest industry, DOE, and National Aeronautics and Space Administration. Principle funding is from USDA, Forest Service, and forest industry.

Recent Progress

- Improved planting stock with better quality wood formation and resistance to insects and diseases.
- Management systems for the efficient production of wood and other valuable products.
- Research programs are in place that can (1) provide an inventory of carbon stocks; (2) understand biological processes; (3) model and predict climate impacts and management strategies, and (4) develop effective, low-cost management systems.
- Partnerships have development among government, university, and private research organizations to better understand, develop, and implement good management practices for carbon sequestration.
- The USDA and DOE are formally collaborating in the Biobased Products and Bioenergy research program to develop more ways to store carbon or use renewable bioenergy to offset carbon emissions.

Commercialization and Deployment Activities

- High-quality planting stock is commercially available.
- Fertilization systems for irrigation and nutrient delivery to individual trees are commercially available.

Market Context

- Development of energy-efficient, low-impact equipment for all forest operations.
- Market for improved planting stock for feedstock production.
- Market entry for resource-efficient durable wood products as substitutions for more energy-intensive products in building.
- Expansion of wood energy feedstocks.
- Potential demand for carbon accounting in forest and wood product production nationally and internationally.
- The market for energy-efficient forest production systems is substantial, nationally and internationally.

3.2.1.4 GRAZING MANAGEMENT

Technology Description

Most grazing land soils can sequester carbon with alternative management technologies and practices. These practices increase the amount of carbon in the soil by increasing biomass production and reducing the amount of carbon lost to erosion. The production of methane by domestic ruminants also can be reduced. Methane production depends on the quality of forage ingested and the efficiency of the digestive process – and can be reduced with improved diet and the use of supplements. These practices increase production efficiency while reducing methane emissions. Environmental and production benefits are high in all cases.

System Concepts

- Increasing carbon storage on grazing lands depends on implementing management technologies (e.g. fire, grazing, seeding) to achieve an appropriate mix of plants that optimize the use of available sunlight, water, and nutrients in biomass production.
- Pasturelands use more fertilizer and water than rangelands, and mesic rangelands have a relatively high sequestration potential.
- Nitrous oxide emissions from fertilizer application on pastures can be dramatically reduced by split applications or applications when plants are actively growing.
- Reduction of methane production by ruminant animals has been demonstrated in grazing systems where improved diet quality and herd management practices have been implemented. In addition, organisms in grassland soils decompose methane into the less-potent greenhouse gas CO_2 and water.

Representative Technologies

- Alternative grazing practice.
- Livestock herd management.
- Vegetation management.
- Water management.
- Erosion control.

Technology Status/Applications

- Each of these technologies has been researched and implemented for purposes other than carbon sequestration, primarily conservation.
- These technologies have generally been demonstrated to be economically feasible.
- Some soil carbon data has been gathered while these practices were investigated for their conservation and yield benefits.

Current Research, Development, and Demonstration

RD&D Goals

- Construct quantitative models that describe site-specific interactions among grazing systems, vegetation, soil and climate, and the effects on greenhouse gas dynamics.
- Develop and optimize the combination of practices that maximize carbon sequestration for various grazing systems and geographical areas.
- Develop decision support tools for ranchers, technical assistance providers, and policy makers to inform the relative costs and benefits of different grassland management scenarios for carbon sequestration and other conservation benefits.
- Demonstrate and refine decision-support tools through pilot projects.

RD&D Challenges

- Develop and implement measurement and monitoring technologies and protocols with sufficient site specificity and acceptable cost-benefit ratios.
- Determine the effectiveness of practices and systems in sequestering carbon.
- Quantify the effects of land and livestock management on carbon sequestration and CO_2, methane, and nitrous oxide emissions across a variety of climates, soils, and production systems.

Recent Progress
• Estimates of the potential for range and pastureland soils to sequester soil carbon have been published and provide a baseline for future activities. • Development of the Pasture Land Management System (PLMS) decision-support tool, a joint project of EPA, National Resources Conservation Service, and Virginia Tech. • Research programs already have been established in the USDA Agricultural Research Service, Natural Resources Conservation Service, Land Grant Universities, DOE, national labs, and U.S. Geological Survey to study soil carbon sequestration. • New technologies for the measurement of greenhouse gas fluxes have been developed.
Commercialization and Deployment Activities
• USDA has provided technical assistance to landowners for implementing these technologies. • Commercial application of grazing land restoration has been successful but is limited in extent. **Market Context** • Virtually 100% of rangeland and grazing lands could increase carbon storage.

3.2.1.5 RESTORATION OF DEGRADED RANGELANDS

Technology Description

Degraded rangelands have low levels of soil carbon and diminished potential for biomass production to increase storage, but represent potentially large carbon sinks. Degradation is usually the result of inappropriate management, especially during extended periods of drought or unusual weather events. Symptoms of degradation include poor soil cover, dominance of undesirable species, low soil quality, or, in the extreme, topsoil erosion. In many arid and semi-arid rangelands, the cost of restoring land may far exceed the potential returns from livestock production. In addition, restoration technologies are unreliable in environments where precipitation is unpredictable. In more mesic areas, many rangelands are occupied by invasive species, which may be native or exotic. Technologies for managing invasive species to increase carbon storage in rangelands are expensive and require significant investment as well as careful post-treatment management.

- Increasing carbon storage on degraded arid and semi-arid rangelands depends on reestablishing vegetation in areas that have lost productivity.
- In many cases, soil may be intact, but beneficial microbial activity has been lost and must be restored simultaneously with vegetation reestablishment.
- In more mesic areas, rangeland degradation is due largely to the dominance of invasive species. The association between increased competition of shrubs and carbon fluxes and other greenhouse gas emissions in rangelands is poorly understood and very difficult to manage.

Representative Technologies

- Reestablishment of vegetation.
- Vegetation management.
- Restoring soil function.

Technology Status/Applications

- Each of these technologies has been researched and implemented for purposes other than carbon sequestration, primarily to prevent erosion and conserve soil.

Current Research, Development, and Demonstration

RD&D Goals

- Gain reliable understanding of the relationship between soil microbes and vegetation establishment and growth in arid and semi-arid areas.
- Develop low-cost, reliable technologies for the restoration of vegetation on degraded arid and semi-arid rangelands.
- Improve decision support for the application of low-cost technologies, such as fire, to control invasive species and to reduce greenhouse gas emissions from mesic rangelands.
- Develop seed production technology to produce low-cost seeds for reestablishing desired rangeland species. Currently costs are high and seed supply is limited for many cultivars.
- Develop new risk management and liability tools for use in prescribed burning systems on rangelands.

RD&D Challenges

- Measuring and monitoring procedures need to be improved for accurate, efficient, and low-cost determination of range and pasture land soil carbon status and determination of the effectiveness of carbon sequestration practices.
- Integrate complex and multisource data to develop better models and decision support systems.
- Develop more accurate estimates of the impacts of these management practices on soil carbon, particularly for the purpose of monitoring carbon sequestration following management adjustments.
- Develop new technologies to restore semi-arid and arid rangelands suffering from degradation, including soil-quality microbe interactions.

Recent Progress

- Estimates of the potential for range and pastureland soils to sequester soil carbon have been published and provide a baseline for future activities.
- Research programs already have been established in the USDA Agricultural Research Service, Natural

Resources Conservation Service, Land Grant Universities, DOE, national labs, and U.S. Geological Survey to study soil carbon sequestration. • New technologies for the measurement of greenhouse gas fluxes have been developed. • New herbicide technologies and fire management practices have the potential to reduce the high costs associated with pretreating restoration sites.
Commercialization and Deployment Activities
• While current costs of rangeland restoration are high, restoration is likely to be economically feasible if there is demand for carbon sequestration. • Currently, the cost of most seeds is high for species and varieties that are needed in grazing land restoration. • USDA has provided technical assistance to landowners for implementing these technologies.

3.2.1.6 WETLAND RESTORATION, MANAGEMENT, AND CARBON SEQUESTRATION

Technology Description

Wetlands, including coastal zones, estuaries and marshes, northern tundra and peatlands, total about 2.8×10^9 ha, about 7% of the Earth's land surface and 11.6% of the United States. Wetlands present an important opportunity for carbon sequestration and greenhouse gas offsets by virtue of their potential for restoration using known and innovative land management methods. Equally important is protection of wetlands in northern and temperate latitudes from carbon loss with global warming. Because they are inherently highly productive and accumulate large below-ground stocks of organic carbon, restoring lost wetlands and protecting those that remain clearly represents an immediate and large opportunity for enhancing terrestrial carbon sequestration.

System Concepts

- Wetlands are inherently among the most productive ecosystems on earth, with 7% of total land area contributing 10% of global net primary productivity.
- Climatic condition is the single most important factor in determining success in protecting carbon stored in existing wetlands. Fire, permafrost melt, sea-level rise and more frequent droughts will significantly affect wetlands.
- Carbon sequestration can be enhanced through application of proven engineered wetlands technology.

Representative Technology or Practices

- Restoration of riparian zones, estuaries and tidal marshes, mangrove forests, bottomland hardwood forests and other wetland systems.
- Management of periodically flooded rice fields and floodplains.
- Protection of existing wetlands, in particular, peatlands, bogs, and other northern latitude wetlands that might otherwise become large sources of gaseous carbon with global warming.

Technology/Practice Status and Application

- Limited data exist as to the actual quantification of sequestered carbon by wetland type and location.
- Wetland restoration has centered on wildlife habitat, water quality improvement, erosion control, shoreline restoration, but not carbon sequestration.
- Efforts to manage northern wetlands in danger of becoming massive sources of carbon to the atmosphere do not exist.

Current Research, Development, and Demonstration

RD&D Goals

- Evaluate the extent to which various management practices on restored wetlands have enhanced carbon sequestration.
- Delineate and quantify carbon stocks in U.S. wetlands by region and type.
- Assess the vulnerability of wetland carbon stocks to human activity and climate change.
- Develop and demonstrate integrated management strategies for wetland carbon sequestration.

RD&D Challenges

- Quantify carbon accrual in wetlands to enable better estimates of their potential for carbon sequestration in coming decades.
- Identify cost-effective management approaches and technologies to mitigate loss of carbon from wetlands in northern latitudes.
- Construct and verify models that couple hydrology, ecosystem processes and carbon sequestration.
- Devise workable fire management techniques for wetlands that are compatible with wildfire suppression strategies.

RD&D Activities

- Ongoing research to evaluate wetland restoration methods.
- Demonstration projects are ongoing in select regions, including the lower Mississippi River valley and delta with mixed results. It has proven difficult to recreate native wetland vegetation assemblages.
- New demonstration projects with industry, including DOE-sponsored work with the Tennessee Valley Authority, have recently been initiated with limited results to date.

Recent Progress
• Wetland loss and degradation has been recognized and new programs implemented to regulate development activities that adversely affect wetland functions. Loss of wetlands in the 1990s was 80% lower than the 1980s. • The U.S. Department of Transportation has established a goal of replacing 1.5 acres for every acre of wetland impacted within 10 years.

3.2.1.7 CARBON SEQUESTRATION ON RECLAIMED MINED LANDS

Technology Description

Hundreds of thousands of hectares of lands are disturbed by extracting minerals, particularly coal, in the United States annually. Topsoils are generally removed prior to mining, resulting in loss of soil organic matter. Stockpiling of the topsoil until it is needed for reclamation of the mined lands also results in a loss of soil organic matter through decomposition with only limited inputs. These degraded lands have a significant potential to sequester carbon once revegetated to grasslands, pastures, cropland, or forest.

System Concepts

- Climatic condition is the single most important factor in determining revegetation success.
- Nearly 1.6 million acres in the Unites States have been affected by mining operations. The soils at these abandoned mining sites only marginally support regrowth of trees and vegetation in the absence of direct management, resulting in erosion and runoff into receiving tributaries.
- Carbon sequestration by these mined lands can be enhanced with organic amendments such as biosolids, sawmill residues, feedlot wastes, and other organic or inorganic byproducts that result in enhanced nutrient status or improved physical characteristics of the restored soil.

Representative Technology or Practices

- Grassland, cropland, and forest restoration on reclaimed or abandoned mine lands.

Technology/Practice Status and Application

- Limited data exist as to the actual quantification of sequestered carbon by reclaimed mined lands.
- These lands should have the potential to sequester carbon at a rate similar to degraded croplands.
- Organic residues have been used on reclaimed mine lands, generally to dispose of the residue rather than consider its benefits in carbon sequestration.

Current Research, Development, and Demonstration

RD&D Goals

- Quantify carbon sequestration on reclaimed mined lands to enable better estimates of the potential of this large land area to sequester carbon.
- Evaluate the extent to which various management practices on reclaimed mined lands enhance carbon sequestration (i.e., measure the effects of organic and inorganic residues, grazing, plant biodiversity, and various shrubs and trees on soil carbon).
- Establish the role of various plant community attributes in carbon sequestration in semi-arid regions of the United States.
- Partner with private organizations and the public sector to sequester carbon and restore impacted lands.
- Develop demonstration projects that promote carbon sequestration and other collateral benefits as primary goals of mine reclamation.

RD&D Challenges

- Establish a sequence of studies across variable climatic zones to adequately address the soil variables, plant community attributes, and response of amendments to the various climatic conditions and management scenarios.

RD&D Activities

- Ongoing research in the eastern U.S. mining regions evaluates the impacts of planting trees to reclaim mined lands and provides estimates of the potential carbon sequestration from this practice.
- Researchers are revising growth and yield models to determine the optimal time of harvest for maximum carbon sequestration.

Recent Progress

- Community-based environmental groups are working with coal and utility companies to reclaim impacted lands, forming successful partnerships.

3.2.2 BIOTECHNOLOGY

3.2.2.1 BIOTECHNOLOGY AND SOIL CARBON

Technology Description

Biotechnology can be used to affect soil carbon by altering the chemical composition of plants and that of microorganisms that control plant decomposition. Plant chemical composition affects the amount of carbon transformed into more stable organic matter (such as humus) when plant biomass decomposes in the soil. Soil microorganisms determine the soil carbon compounds that are formed during residue decomposition.

System Concepts

- Roots and wood that have relatively high lignin content are more readily converted into stable soil organic matter than are plant components with high cellulose and hemicellulose content. Cellulose and hemicellulose are more readily decomposed by soil microbial respiration and released to the atmosphere as CO_2.
- Soil microorganisms that control plant decomposition also produce chemical precursors to stable organic compounds. Thus, genetic modifications that increase soil microorganism production of these chemical precursors could potentially affect soil carbon content.
- Use of genetically modified crops to enhance yields and reduce fertilizer.

Representative Technologies

- Plants already have been modified using biotechnological methods for herbicide resistance, to produce an insecticide, and to produce vitamin A precursors.
- Microorganisms have been bioengineered to produce novel compounds (e.g., insulin) and to biodegrade recalitrant compounds present in hazardous wastes.
- Herbicide tolerant crops that advance conservation tillage.
- Genetically modified crops that increase utilization of soil nutrients and/or fertilizer.
- Technologies that increase agricultural productivity (e.g., by increasing yields or minimizing spoilage and increasing shelf life, because each would minimize area under cultivation).

Technology Status/Applications

- Biotechnology has successfully produced modified plants and microorganisms, but it has not been used to modify plants or microorganisms to enhance soil carbon sequestration.
- This technology may be better suited for biomass/bioenergy crops than traditional food and feed crops because of the close compatibility between plant characteristics and desired biomass/bioenergy crop properties.

Current Research, Development, and Demonstration

RD&D Goals

- Identify the traits needed in plants and microorganisms to increase soil carbon sequestration capacity.
- Determine the feasibility of using biotechnology to modify the traits of plants and microorganisms that can affect soil carbon sequestration.
- Develop systems for monitoring nontarget environmental affects associated with plant modifications.
- Develop methods to incorporate genetically modified plant and microorganisms into cropland and conservation reserve and buffers systems.
- Develop guidance for farmers, other land managers, and policy makers for using carbon sequestration biotechnology products.

RD&D Challenges

- Because biotechnology has not yet been used to enhance soil carbon sequestration, the feasibility of this approach is unknown. In particular, specific genetic traits affecting carbon sequestration capacity need to be evaluated to determine whether few or many genes are involved and how modifications to these traits might also impact crop yields.
- Estimate the costs of bioengineered plants and microorganism, which may be prohibitive for farmers, ranchers, and other managers.
- Determine whether modified microorganisms can compete with native microflora.
- Address the general concern of introducing genetically modified organisms into ecosystems because of their potential to disrupt natural ecosystem processes.

Recent Progress
• Biotechnology has been used to successfully modify plants and microorganisms for other purposes.
Commercialization and Deployment Activities
• Both private companies and public research agencies have biotechnology products in commercial markets. • Regulatory procedures are in place for release of genetically modified organisms. • The private sector will support the development of carbon sequestration biotechnology if the market is large enough. **Market Context** • Difficult to estimate until feasibility research is conducted.

3.2.3 IMPROVED MEASUREMENT AND MONITORING

3.2.3.1 TERRESTRIAL SENSORS, MEASUREMENTS, AND MODELING

Technology Description

Agricultural lands (cropland, pasture, rangeland) represent potentially large and cost-effective sinks for atmospheric carbon, if management technologies can be applied in the right place at the right time. Management to increase carbon sequestration requires the development of more sophisticated, lower-cost measurement systems and models for integrating multiple data sources into a decision-making context.

System Concepts

- In the past, management of soil carbon and greenhouse gas (GHG) emissions has not been a primary management goal in agriculture. Consequently, efforts to develop rigorous quantification systems at multiple scales (local, regional national) are relatively recent, but are rapidly developing.
- Methods exist to accurately and precisely measure soil carbon and GHG concentrations and fluxes. However, most conventional methods were developed for local measurements. Plot and field applications and numerous samples must be analyzed for accurate and precise values.
- Models (particularly computer simulations) of soil carbon and GHG dynamics exist and several are in widespread use and have been extensively tested against research data. Their development and use in inventories, policy assessment, and decision-support environments is only recent.
- Emergence of new sensing technologies (i.e. laser, infrared, multispectral video) and computing power capable of handling large amounts of information has spawned a new generation of instruments, databases, and computer models.
- There is a rich collection of resource data on factors determining soil carbon and GHG dynamics in croplands, e.g., survey data on management practices, crop areas and yields, soil maps, land cover, and irrigation. Much of the data is spatially referenced and can be used to drive stimulation models and interpolate/extrapolate measurements. Similar data exists for grazing lands, with the exception of type, distribution, and extent of different management practices for which information is currently sparse.

Representative Technologies

- Instruments to measure GHG fluxes among soils, plants, animals, and the atmosphere.
- Models to integrate spatial and temporal variability into a decision context.
- Easily accessible, interactive distribution systems of quantification technologies that integrate measurement and modeling approaches.

Technology Status/Applications

- New sensors, instruments, measurement systems, models, and distribution systems are emerging, but integrated systems of information collection, retrieval, management, manipulation, and processing to aid decision making in complex and diverse agricultural environments have yet to be developed.
- Integrated information management and the physical sciences now have the capacity to provide vastly improved information to land managers and policy makers to improve the amount of carbon stored in grazing land soils.

Current Research, Development, and Demonstration

RD&D Goals

- Develop a new generation of sensors and instruments to measure GHGs and their fluxes in situ across a wide variety of agricultural ecosystems.
- Develop cost-effective soil carbon probes for in situ measurement of soil carbon content (as opposed to fluxes) that can be made both before and after implementation of management changes to validate impacts on sequestration.
- Determine time and cost-efficient sampling and monitoring designs to support national inventories and project level GHG mitigation activities.
- Combine measurement technologies and ecological process models to make reliable predictions (and verify them) regarding the impact of management on GHG dynamics.
- Integrate near real-time climate information into process models as a driver.

- Distribute site-specific information to farmers, ranchers, and technical assistance providers to aid in making more realistic decisions.

RD&D Challenges

- High spatial and temporal variability results in very complex situations that must be measured and modeled. Data sources will be multisource and large.
- Successful implementation will require substantial improvements in the ability of field staff and land managers (farmers and ranchers) to use complex information.

Recent Progress

- Laser-induced breakdown spectroscopy instrument to measure soil carbon in situ for less than 10% of the lab costs of other methods with comparable reliability.
- Mid-range infrared spectroscopy to measure soil carbon and forms.
- Near-infrared spectroscopy technology and Nutritional Balancer software to accurately predict livestock diet quality based on fecal analysis.
- Biophysical models have been developed to integrate spatial and temporal variability in soils into a predictive framework for making estimates of changes in soil carbon in response to climate and management.
- Satellite and low-altitude remote-sensing technologies have been developed that can quantify cropland and grassland features at a spatial resolution of less than 0.5 m^2.
- Internet distributed site-specific information systems that integrate near real-time weather predictions, land condition, and land-cover classes have been developed. Such tools provide ready access to information used in developing decision tools and in dynamic models as inputs.
- Decision-support systems are being developed that can integrate information to evaluate implications of various management decisions.

Commercialization and Deployment Activities

- Markets in precision agriculture and decision-support consultation are potentially large.
- Technical basis of instruments, models, and information systems is proven, but their systematic deployment to solve complex problems remains unexplored.

3.2.3.2 MEASURING AND MONITORING SYSTEMS FOR FORESTS

Technology Description

Forest systems provide a significant carbon sink and can contribute to GHG emissions. To mitigate GHG effects, advanced technology is needed to measure and monitor forest and wood product processes, pools, and fluxes to better manage these systems to reduce and mitigate emissions, and to enhance carbon sinks. Measurement systems should be integrated using a multitiered approach combining national inventories, remote sensing, land-based measurements, and intensive monitoring on experimental sites. Additional profiles on measuring and monitoring systems for greenhouse gases in general can be found under "Enhancing Capabilities to Measure and Monitor Emissions."

System Concepts

- GHG (fluxes and pools) inventory and measurement systems are a collage of measurements, covering broad temporal and spatial scales, methods, and technologies. No current inventory system provides the comprehensive coverage across scales needed to understand and manage GHG across the United States.
- An integrated approach is needed that combines national inventories, remote-sensing data, regional and site studies and measurements, experimental data, and modeling capabilities into a comprehensive observational and analysis system.
- Technology advances are needed in (1) enhanced remote-sensing data collection and analysis, (2) expansions and enhancements of extensive inventories systems for large-scale, landscape, and integrated resource measurements, (3) in situ instrumentation and monitoring systems for intensive monitoring, (4) specialized measurement and characterization systems for soils, and (5) integrating measurements and data.
- Global positioning and inertial measurement infrastructure, and remote and in situ sensors for soil, plant and microclimate characterization and monitoring

Representative Technologies

- The USDA Forest Service's Forest Inventory and Analysis Program and the Natural Resources Conservation Services' National Resources Inventory provide the basis for a national carbon inventory and annual changes in carbon pools for forest, pastures, and croplands.
- Wide range of technology such as global positioning systems, satellite and aircraft based remote sensing, in situ electrical, magnetic, optical, chemical, and biological sensors, and scientific instruments.

Technology Status/Applications

- LIDAR and RADAR remote-sensing methods are being developed and tested for 3-D imaging of forest structure. Additional work is needed to integrate remote and land-based measurements.
- Low-cost, portable, real-time measurement systems are not available for soil monitoring and other in situ measurements.

Current Research, Development, and Demonstration

RD&D Goals

- Reduce uncertainty associated with the national carbon inventory by improving coverage of national inventories and analyses of changes.
- Develop understanding of underlying processes of biological and ecological processes in order to develop improved monitoring systems and use systems to validate models for mitigation actions.
- Improve and develop low-cost, portable, real-time sensors and measuring systems for in situ measurements.
- Provide integration and systems design of remote sensing and ground-based carbon pool and GHG fluxes measurements technology using multitiered system.

RD&D Challenges

- National inventory systems were not designed for carbon and other GHG measurements and have not been adequately supported to develop complete wall-to-wall, comprehensive inventories of carbon pools and fluxes among the pools and atmosphere.
- There is little understanding of forest soil processes in the storage and allocation of carbon. This information is paramount for the development of management systems and practices that enhance carbon sequestration.

- The broad range of required scales, cover types, and ecosystems will require the development of (1) remote sensing integrated with other measurements at various levels of coverage, duration, and intensity, and (2) low-cost, robust measurement systems that can effectively be used at different scales. Sites covered need to be expanded as part of extensive monitoring and intensive measurement systems.
- A great wealth of information and data will be acquired by enhanced measurement and monitoring systems. Advances are needed in the technology to manage, process, translate, analyze, and transform this information into predictive and decision-making tools.
- Develop measuring and monitoring systems for carbon pools in wood products in use and in landfills.

RD&D Activities

- Efforts are underway to improve carbon inventory systems and reduce the uncertainty of our national inventory.
- Improvements are being made in remote sensing, senor, instrumentation, and measuring system technology through Federal, university, and private collaboration.
- Current technology needs to be more fully deployed; and new, innovative technology should be piloted and demonstrated to accelerate deployment.

Recent Progress

- The USDA Forest Inventory and Analysis Program assesses the U.S. forest structure and condition and is the basis for our nation's carbon inventory in concert with information provided by the National Resource Inventory. Periodic national carbon inventories have been produced using this data.
- The AmeriFlux network is being completed, which will improve the understanding of carbon pools and fluxes in large-scale, long-term monitoring areas and intensive experimental sites.
- Research programs are in place that can (1) provide inventory of carbon stocks, (2) understand and quantify biological processes, (3) model and predict climate impacts and management strategies, and (4) develop effective, low-cost management systems.
- Partnerships have developed among government, university, and private research organizations to improve greenhouse gas measurements.

Commercialization and Deployment Activities

- Global positioning systems are currently in use and can provide geo-references for carbon measurements.
- Current technology is not fully deployed; efforts are needed to demonstrate and increase the efficiency of such technologies.
- Specialized remote sensing technology is being developed and will be deployed in the near term for the measurement of greenhouse gas emissions and carbon stocks.
- A comprehensive, integrated, multiple-tier measuring and monitoring system needs to be fully developed and deployed.

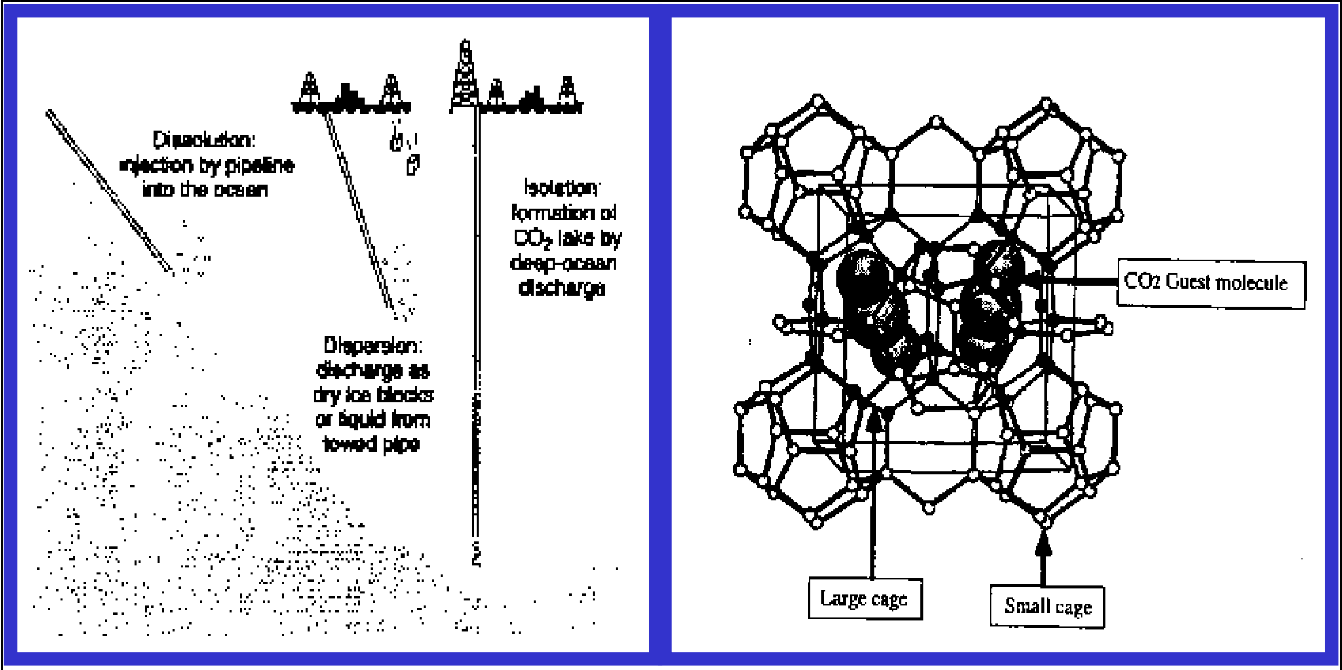
Market Context

- Improved technology for carbon measurements can provide security in credit trading.
- Enhanced measurement systems can provide input for the optimal design, deployment, and management of forest and wood product systems that will provide additional carbon sequestered and ancillary benefits.

3.3 OCEAN SEQUESTRATION

3.3.1 OCEAN SEQUESTRATION – DIRECT INJECTION

Technology Description



Sketch of various ocean CO_2 disposal options (left). Structure of a CO_2 hydrate (right).

Ocean sequestration technologies strive to reduce carbon emissions by injecting captured CO_2 into the ocean, rather than releasing it into the atmosphere. The captured CO_2 is concentrated, and then pressurized into a liquid state. The physical chemistry of CO_2 is such that at high pressure and low temperatures (which exist at depth in the ocean), the CO_2 molecule reacts with seawater wrapping itself in a cage of water to form a solid compound much like ice (clathrate). This reaction profoundly changes its behavior. However, there are significant environmental questions that need to be examined.

System Concepts

- CO_2 is captured from a large point source of anthropogenic emissions, transported, and injected into the ocean via pipeline or tanker.
- CO_2 molecule reacts with seawater wrapping itself in a cage of water to form a solid compound much like ice (clathrate).

Representative Technologies

- Technologies will potentially be borrowed from the petroleum industry in the areas of drilling simulation and wells; processing, compression, and pipeline transport of gases; and operational experience of CO_2 injection.

Technology Status/Applications

- The injection technology is technically ready for adaptation for mid- to deep-ocean injection. However, technology is not ready for deployment. This is due to insufficient data detailing hydrate interactions with marine community structure, as well as knowledge gaps about physical and chemical behavior concerning dispersion and transport of hydrate plume by ocean hydrology.

Current Research, Development, and Demonstration

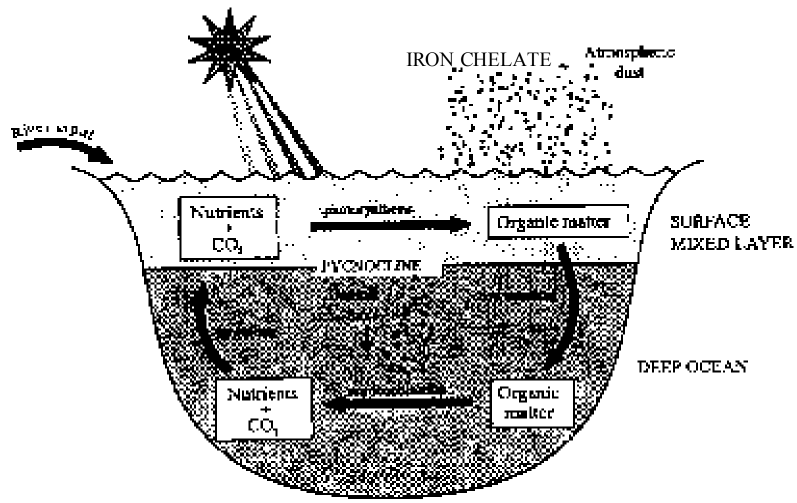
RD&D Goals

- Demonstrate that CO_2 direct injection is safe and environmentally acceptable.
- Improve global circulation simulation with more accurate biology modules.

RD&D Challenges
RD&D Challenges • Develop field practices that optimize CO_2 direct-injection retention times. • Develop the ability to predict plume effects on marine organisms. • Develop the ability to track the fate of direct injected CO_2. • Develop a better understanding of the CO_2 chemistry in ocean waters, and its effects on indigenous organisms, e.g. hypercapnia (effects of elevated CO_2 levels), and acidification of plume waters (depressed pH). **RD&D Activities** • Key DOE activities are targeted to determine physical, chemical and biological impact of direct injection. • Conduct an appropriate-scale field experiment to adequate assess unit operations and potential impacts on marine environment at a sufficient scale downstream of injection zone. • Formulate future experiments to evaluate community effects (long term) and the total impact on the ecology of multiple regions of deep oceans. • Develop other small-scale field experiments to understand fundamental biogeochemical cycles**.** • Current expenditures for field experiment estimated to be $6 million.
Recent Progress
• A survey cruise of Hawaiian biology occurred during the summer of 1999. • Small-scale release (one liter) at 3,600 m off the California coast demonstrating hydrate formation. • Properties of hydrate formation determined in lab utilizing high-pressure, low-temperature reaction vessels. • Conducted 10-day cruise off Loihi seamount (Hawaii) during December 2002, to determine effect of natural analogues of CO_2 on amphipod community in vent waters**.**

3.3.2 OCEAN SEQUESTRATION – IRON FERTILIZATION

Technology Description



CONCEPT OF IRON FERTILIZATON

It is hypothesized that the rate of carbon dioxide fixation by microscopic plants called phytoplankton that live in the surface waters of the oceans may be limited by the availability of iron. In particular, field experiments in high nutrient, low chlorophyll (a measure of plant biomass) ocean waters such as the Southern Ocean and the Equatorial Pacific have shown that addition of iron increased the rate of removal of carbon dioxide through the process of photosynthesis. The carbon dioxide has thus been incorporated into plant biomass (phytoplankton), some of which will sink to deeper waters (export) where it may be sequestered for a period of time. Industry has developed a strong interest in using iron fertilization as a potentially low cost technology to offset carbon dioxide emissions. Many fundamental questions, however, remain as to the long-term effectiveness and potential environmental consequences of this carbon sequestration strategy.

System Concepts

- Iron chelate "fertilizer" is mixed into the ocean via vessel propellers. The release stimulates phytoplankton bloom.
- The phytoplankton bloom increases the rate of carbon fixation or photosynthesis, thus reducing the levels of carbon dioxide dissolved in the surface waters. Having converted carbon dioxide to plant biomass, some of the phytoplankton will sink to deeper waters where the carbon will be sequestered.

Representative Technologies

- Technologies will be borrowed extensively from the unit operations of the maritime industry and existing instrumentation systems.

Technology Status/Applications

- Three previous research demonstrations have been performed. The Southern Ocean Iron Fertilization Experiment (SOFEX) occurred in January-February 2002. This research, which was cofunded by the National Science Foundation and the Department of Energy, aims to quantify carbon export – that is, how much carbon sinks to deeper waters, after fertilization with iron. The major goal is to quantify the extent of export production of carbon.

Current Research, Development, and Demonstration

RD&D Goals

- Determine if iron-induced phytoplankton blooms result in the vertical flux (transport) of carbon from the surface waters (export production) to the deep waters.

RD&D Challenges

- Determine the overall short-term environmental consequences of release of iron as iron chelate.
- Determine the long-term consequences of iron enrichment on the surface water community, midwater community, and ocean processes.
- Determine the best proxy for carbon.
- Quantify the efficiency of the long-term storage of carbon.

RD&D Activities
• Continue data reduction from SOFEX cruise. • Determine magnitude of carbon export from surface layer from SOFEX. • Prepare for proposal selection from current solicitation.
Recent Progress
• Previous cruises of research vessels IRONEX I and II, and SOIREE, confirmed the stimulation of phytoplankton bloom by the addition of iron chelate.